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Calibration of ^{192}Ir high dose rate brachytherapy source using different calibration procedures

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ABSTRACT

Aim: To calibrate Ir-192 high dose rate (HDR) brachytherapy source using different calibration methods and to determine the accuracy and suitability of each method for routine calibrations.

Background: The source calibration is an essential part of the quality assurance programme for dosimetry of brachytherapy sources. The clinical use of brachytherapy source requires an independent measurement of the air kerma strength according to the recommendations of medical physics societies.

Materials and methods: The Ir-192 HDR brachytherapy source from Gammamed plus machine (Varian Medical Systems, Palo Alto, CA) was calibrated using three different procedures, one using the well-type ionization chamber, second by the in-air calibration method and third using solid water phantoms. The reference air kerma rate (RAKR) of the source was determined using Deutsche Gesellschaft fur Medizinische Physik (DGMP) recommendations.

Results: The RAKR determined using different calibration methods are in good agreement with the manufacturer stated value. The mean percentage variations of 0.21, −0.94, −0.62 and 0.58 in RAKR values with respect to the manufacturer quoted values were observed with the well-type chamber, in-air calibration, cylindrical phantom and slab phantom measurements, respectively.

Conclusion: Measurements with a well-type chamber are relatively simple to perform. For in-air measurements, the indigenously designed calibration jig provides an accurate positioning of the source and chamber with minimum scatter contribution. The slab phantom system has an advantage that no additional phantom and chamber are required other than those used for external beam therapy dosimetry. All the methods of calibration discussed in this study are effective to be used for routine calibration purposes.

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1. Background

Brachytherapy is considered as an essential part of the treatment for almost all the sites of cancers.[1] High Dose Rate (HDR) brachytherapy has been widely accepted over the past two decades, particularly for the treatment of gynaecological tumours and for tumours at other sites which are not easily accessible for Low Dose Rate (LDR) techniques. With the improved localization techniques and advanced treatment planning systems, it is now possible to have precise and reproducible dose delivery. However, desired clinical results can only be achieved with a good clinical and dosimetric practice.

The clinical use of brachytherapy source requires an independent measurement of the air kerma strength according to the recommendations of the medical physics societies. The recommended quantity by International Atomic Energy Agency (IAEA)[2] for the specification of gamma sources is the reference air kerma rate (RAKR), defined by the ICRU[3–5] as the kerma rate to air, in air, at a reference distance of 1 m, corrected for air attenuation and scattering. The Netherlands Commission on Radiation Dosimetry (NCS)[6] states that the uncertainty in dose specification for brachytherapy due to physical procedures should be less than ±5%. The calibration certificate issued by the manufacturer quotes source strength with an overall uncertainty of ±5%. Hence, calibration of brachytherapy source at the user level is necessary not only to check manufacturer stated calibration but to ensure traceability to internationally accepted standards.[1,2]

The American Association of Physicists in Medicine (AAPM) states that any institution planning to provide brachytherapy should have the ability to independently verify the source strength provided by the manufacturer.[7] A benchmark data set of brachytherapy HDR and pulsed dose rate (PDR) quality control (QC) testing has been presented by a comprehensive survey undertaken in the United Kingdom (UK) radiotherapy centres which is representative of practice across the UK.[8] Calibration of ^{192}Ir source is generally performed using a well-type ionization chamber or a cylindrical ionization chamber. But the Task Group for Afterloading Dosimetry of the Deutsche Gesellschaft fur Medizinische Physik (DGMP) recommends specially calibrated solid-state phantoms which can provide higher reproducibility and better accuracy in calibration of brachytherapy sources.[9] A study conducted to compare the results of the three years of HDR and PDR source activity control procedure showed that dosimetry systems using well-chamber and thimble chamber are fast and reliable tools for checking ^{192}Ir source parameters in working brachytherapy departments.[10]

2. Aim

The aim of the present study was to calibrate ^{192}Ir high dose rate (HDR) brachytherapy source using different calibration methods and to determine the accuracy and suitability of each method for routine calibrations. The second purpose was to determine the accuracies of the different methods with reference to the well-type chamber measurements.

3. Materials and methods

The Gammamed Plus ^{192}Ir source from Gammamed plus machine (Varian Medical Systems, inc., Palo Alto, CA) is 4.52 mm long with an active length of 3.5 mm. The source capsule has an outer diameter of 0.9 mm, active diameter of 0.6 mm and a stainless steel encapsulation. The source was calibrated using three different procedures, one using the recommended well-type chamber, second by the in-air calibration method and third by using solid phantoms. Two types of solid phantoms were used; a cylindrical PMMA phantom and a solid phantom of white polystyrene slabs. Each method of calibration was repeated periodically ($n = 6$) to verify the consistency in the readings.

The technical specifications of the ionization chambers used in this study are given in Table 1. The calibration procedures using each of the above mentioned methods are discussed below.

3.1. *Well-type ionization chamber*

The use of a well-type ionization chamber for HDR source calibration is the recommended procedure by AAPM[11] to simplify the calibration process and it has been evaluated by several authors.[12–16] The well-type re-entrant chamber used for the present study is hermetically sealed and contains pure Argon as the fill gas at a pressure of 23.5 psi. The chamber has a diameter of 17.0 cm and 31.3 cm height with an active volume of 1.2 L.

The measurement setup is shown in Fig. 1. The RAKR using a well-type chamber[1,2,16] can be determined from the following expression,

$$(K_a)_a = N_k K_p I_{max} K_{ion}$$

where N_k is the air kerma strength calibration factor given in Gy m^2 h^{-1} A^{-1} at 1 m and taken from the calibration certificate provided by the calibration laboratory. The calibration factor for the well-type chamber used was 7.562×10^4 Gy m^2 h^{-1} A^{-1} at 1 m.

K_p is the correction factor for the change in the temperature and air pressure from the reference chamber calibration

Fig. 1 – RAKR measurement set-up with well-type re-entrant chamber.

Table 1 – Technical specifications of each ionization chamber.

Parameter	Well-type chamber	Ionization chambers	
		FC-65 G	RK-chamber
Manufacturer	Capintec, USA	Scanditronix/Wellhofer	Scanditronix/Wellhofer
Type	Hermetically sealed	Vented to atmosphere	Vented to atmosphere
Active volume (cc)	1200	0.65	0.12
Height/length (cm)	31.3	2.30	1.0
Diameter (cm)	17.0	0.71	0.12
Wall material	–	Graphite	PMMA
Wall thickness (g/cm^2)	–	0.07	0.12
Bias voltage (V)	500	300	400

conditions. Since the re-entrant chamber is hermetically sealed the K_p correction was not required.

I_{max} is the maximum measured ionization current with the well-type chamber given in nA.

K_{ion} is the reciprocal of the ion collection efficiency factor A_{ion}

$$A_{ion} = \frac{4}{3} - \frac{1}{3} \cdot \frac{Q_1}{Q_2}$$

where Q_1 and Q_2 are the charge readings at nominal voltage (300 V) and half voltage (150 V), respectively.

4. In-air calibration

Calibration of brachytherapy source can also be performed using Farmer-type ionization chambers in air by the multiple-distance method. The in-air method has been discussed in the literature by several authors.[15,17–19] The ionization chamber used must have a recommended wall thickness (0.31 g/cm^2) to provide charge particle equilibrium for the photons emitted by ^{192}Ir source.[15] The 0.65 cc volume cylindrical ionization chamber (FC-65G, Scanditronix/Wellhofer) with a total (wall + build-up cap) wall thickness of 0.631 g/cm^2 and Dose1 electrometer (Scanditronix/Wellhofer) were used for the present study. An indigenously designed jig with provisions to hold the chamber and fix the source applicator at various distances from the chamber was fabricated for the experiment. The experimental setup is shown in Fig. 2.

The jig was placed at a distance of at least 1 m above the floor at the centre of the room and at 1 m distance from any of the walls. The chamber with the build-up cap was fixed at one end of the jig while the applicator needle was moved to various distances (10, 15, 20, 25, 30, 35 and 40 cm) from the chamber. Initially, metre readings were noted by moving the source to different dwell positions with a step size of 5 mm vertically along the applicator to determine the maximum sensitive dwell position. The source was placed at this reference distance for air kerma measurements. The measured charge for a time interval t (s) was corrected for ambient temperature and pressure, ion recombination, air attenuation, non uniform electron fluence within the air cavity[2,20,21] and attenuation in the applicator. No correction for transit time was made as the electrometer measurement was initiated after the source stopped moving.

Fig. 2 – Experimental set-up for in-air measurements.

The RAKR of the source was determined using the DGMP recommendations[8,22] as follows:

$$(K_a)_a = \frac{1}{1-g_a}\left(\frac{\mu_{en}}{\rho}\right)_{a-w} N_{DW} k_Q k_r k_{AK} A_w f$$

where N_{DW} is the calibration factor of the ionization chamber for ^{60}Co beam in terms of absorbed dose to water.

g_a is the fraction of energy of the secondary electrons, which is lost in bremsstrahlung

$(\mu_{en})/\rho_{a-w}$ is the ratio of mass energy absorption coefficients for air and water. The spectrum-weighted value for ^{192}Ir source is 0.899.

k_Q is the beam quality correction factor, which accounts for the differences in the energy spectrum of the reference photon beam (usually ^{60}Co) for which chamber has been calibrated. Since the energy dependence of modern thimble chambers is marginal[22] a value of 1.0 is used.

$k_r = (1/r_0^2)$, is the inverse square correction factor, where r_0 is the reference distance of 1 m.

k_{AK} is the correction factor for application of Co-60 build-up cap. A value $k_{AK} = 1.005$ is recommended.[22]

A_w is the chamber wall correction factor which corrects for the attenuation and scattering in the wall of an ionization chamber.[23] A_w can be determined using the relation $A_w \approx 1 - \gamma t$, where γ is the attenuation and scattering fraction per wall thickness (cm^2/g) and taken as 0.0277 and t is the total thickness (g/cm^2) of wall material. The calculated value of A_w for the 0.65 cc chamber is 0.98028.

f is the proportionality constant calculated from the following expression:

$$(M_d - M_s) \propto \frac{1}{(d+c)^2}$$

Fig. 3 – RAKR measurement set-up with cylindrical phantom and 0.12 cc ionization chamber.

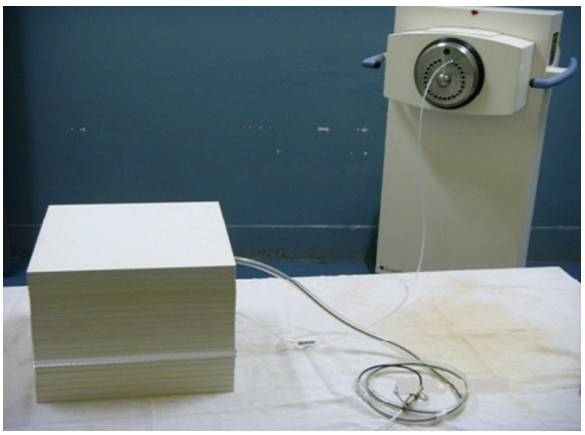

Fig. 4 – RAKR measurement set-up with solid phantom and 0.65 cc ionization chamber.

or

$$f = (M_d - M_s)(d + c)^2$$

where M_d is the corrected air kerma reading which is the sum of primary and secondary radiation contributions, i.e., $M_d = M_p + M_s$. d is the nominal distance between the centre of the source and the centre of the chamber and c is the error in the measurement of nominal distance d. The scatter contribution M_s was determined by an iterative method using the Seven-distance method.[15]

5. Solid phantoms

This is an alternative approach to the calibration of ^{192}Ir HDR source. Two types of solid phantoms were used for the measurements:

(i) **Cylindrical phantom**: The PMMA phantom has a diameter of 20 cm and a height of 12 cm. The measurements were performed using 0.12 cc chamber (R-K chamber Scanditronix/Wellhofer) and RDM-1F (Therados) electrometer. The ionization chamber was placed within 4 holes at 8.0 cm distance from the source and at 0°, 90°, 180° and 270° angles. The measurement setup is shown in Fig. 3. The source was made to dwell in a nylon catheter positioned centrally in the phantom.

(ii) **Slab phantom**: It is a 30 cm × 30 cm white polystyrene phantom with a total height of 22 cm as shown in Fig. 4. The chamber was placed at a distance of 10 cm from the source. The 0.65 cc cylindrical ionization chamber (FC-65G, Scanditronix/Wellhofer) and Dose1 electrometer (Scanditronix/Wellhofer) were used for the air kerma measurements.

The RAKR of the source was determined according to the DGMP recommendations as follows:

$$(K_a)_a = \frac{1}{1 - g_a}\left(\frac{\mu_{en}}{\rho}\right)_{a-w} k_{w\to p} k_{ph} k_\tau k_p k_r k_Q N_{Dw} M$$

where $k_{w\to p}$ is the perturbation factor for changing from water to polystyrene medium. A value of 1.0 was assumed in this study.

k_{ph} is the correction factor which accounts for the absorption and scattering effects due to the presence of the phantom. A value of 1.187 was taken for the cylindrical phantom[16] and 1.1303 is used for the slab phantom.

$k_\tau = 60/\tau$ is a factor to extrapolate the reading to per hour and τ is the read out time in minutes.

$k_r = (r_m/r_0)^2$, where r_m is the measurement distance. For cylindrical phantom r_m is 8 cm and for slab phantom it is 10 cm. r_0 is the reference distance of 1 m.

M is the average metre reading. For cylindrical phantom, M is the average of the readings taken at 0°, 90°, 180° and 270° radial distances.

6. Results

The response of the well-type chamber at various positions from the bottom of the chamber was measured with a step size of 5 mm. The graph of chamber response vs. dwell position is shown in Fig. 5. The maximum response was observed at the first position from the chamber bottom. The width of the region of uniform response (plateau region) of the sensitivity curve is found to be 15 mm with 0.07% variation in relative ionization. The electrode design features a gap of 1 cm between

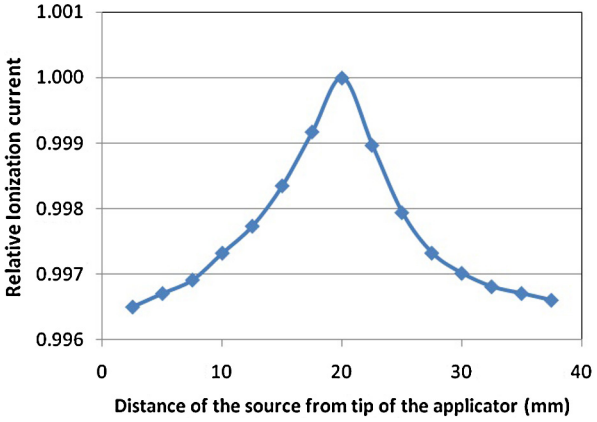

Fig. 5 – Graph of well-type chamber response vs source dwell position.

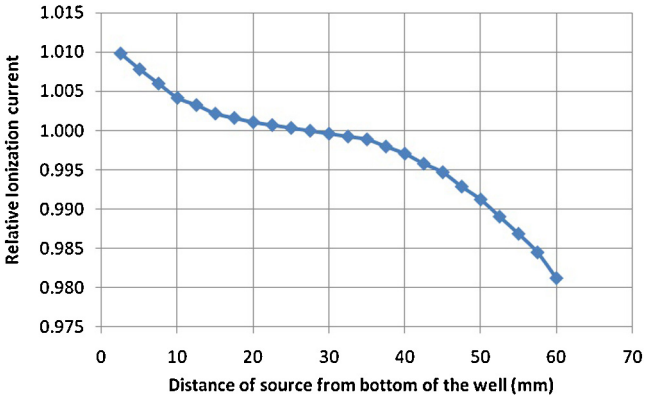

Fig. 6 – Variation of 0.65 cc ionization chamber response with source dwell position.

Table 2 – Mean percentage deviation (ranges of deviation) of measured RAKR for each calibration method from the manufacturer specified value for each method performed six times.

Calibration method	Percentage deviation
Well-type chamber	0.21 ± 0.20 (−0.19 to 0.36)
In-air measurement	−0.94 ± 0.42 (−1.5 to −0.6)
Cylindrical phantom	−0.62 ± 0.55 (−1.28 to 0.36)
Slab phantom	0.58 ± 0.46 (−0.12 to 1.02)

the well and the collector. This electrode separation results in extra sensitivity at the bottom of the well. This is the reason for the asymmetric axial response curve with a flat region rather than the conventional parabolic axial response curve generally observed in the cylindrical geometry of well chambers.[13] The RAKR determined using the well-type chamber was in good agreement with the manufacturer provided value.

For in-air measurements, the 0.65 cc ionization chamber with a build-up cap of thickness 0.55 gm/cm^2 was used. The variation in the response of the chamber with the source dwell position (5 mm step size) from the tip of the applicator needle is shown in Fig. 6. The maximum response was observed at about 15 mm from the tip of the chamber. Initially, there is an increase in the response which attains the peak value after which there is a steep fall in the chamber response.

The results of the RAKR measurements using different calibration methods are shown in Table 2. Table shows the percentage variation in RAKR values using each method with respect to the values quoted by the manufacturer. The percentage difference in the RAKR values obtained from each calibration procedure taking the well-type chamber as reference is given in Table 3.

Table 3 – Percentage difference in the RAKR values obtained from each calibration procedure taking well-type chamber as the reference.

Calibration method	RAKR (mGy m^{-2} h^{-1})	% Deviation
In-air measurement	38.50	−0.96
Cylindrical phantom	38.48	−1.00
Slab phantom	39.16	0.75

7. Discussion

The beam quality correction factor k_Q was assumed to be 1.0 in the present study. Baltas et al.[16] studied the photon energy dependence of the calibration factors N_{DW} and N_k for 0.3 cm^3 rigid stem ionization chamber. It was observed that the energy dependence of the response of the compact cylindrical chambers for energies above 300-kVp to Co-60 is very low so that the k_Q factor of 1.0 for ^{192}Ir could be within an error of 1%. Hence, the DGMP protocol recommends the use of cylindrical compact ionization chambers and also accepts the k_Q factor of 1.0 for modern thimble chambers.[22]

The applicator attenuation correction factor was determined assuming the stainless steel 1.4401 (AISI 316) of the applicator needle to be equivalent to stainless steel ANSI 303/304. The effective attenuation coefficient μ_{eff} of ANSI 303/304 is 0.03 ± 0.004 mm^{-1} [16] and the wall thickness of the applicator needle used in our study is 0.15 mm, from which applicator attenuation is estimated to be 0.9955. Hence, a correction factor of 1.0045 was used to correct for the attenuation of the metallic applicator.

The phantom correction factor for the slab phantom was determined by taking well-type chamber readings obtained during the initial calibration as reference. A value of 1.1303 was obtained which was used to correct for the effects of scattering and absorption due to the presence of a solid slab water phantom. For cylindrical phantom, a value of 1.187 was taken.[16] The advantage of using a solid phantom for brachytherapy source calibrations is that measurements in such a phantom do not require a scatter free environment, i.e., they can be performed in any room designed for the application of HDR sources. Also the source-detector geometry in a solid phantom can be maintained easily in comparison to the setup for in-air measurements. Hence, calibrations can be performed more precisely with solid phantoms.[24]

An uncertainty exists in the position of the source within the metallic applicator. The inner diameter of the dosimetry applicator is 1.35 mm and the outer diameter of the ^{192}Ir source is 0.9 mm. Hence, the source can displace a maximum of ± 0.22 mm with respect to the central axis of the applicator. The uncertainty in the determination of calibration factor (N_k) reported by the secondary standard dosimetry laboratory (SSDL) is 3% at the 95% confidence level (2σ) for the well-type chamber and CNMC electrometer. Similarly, the uncertainty reported in the determination of calibration factor N_{DW} by the SSDL is 1.5% at the 95% confidence level (2σ) for the 0.65 cc chamber with Dose1 electrometer and the 0.12 cc chamber with RDM-1F electrometer. The charge leakage associated are less than 10^{-12} for the well-type chamber, 0.15% for the 0.65 cc chamber and 0.01% for the 0.12 cc chamber, respectively.

8. Conclusion

A good agreement is seen between the measured and the manufacturer quoted RAKR values with each method of calibration. Measurements with a well-type chamber are relatively simple and quick to perform, provided a source positioning is accurate. For in-air measurements, the indigenously designed calibration jig provides better and more accurate positioning

of the source and chamber while also contributing minimum scatter radiation. Also, apart from the calibration jig, no special equipment is necessary because the ionization chamber used for external beam therapy dosimetry. The slab phantom system has an advantage that no additional phantom and chamber are required other than those used for external beam therapy dosimetry. The comparisons of in-phantom and in-air measurements indicate that in-phantom measurements are easy to perform and can be an alternative to in-air calibrations. All the methods of calibration of HDR brachytherapy source discussed in this study are effective to be used for routine calibration purposes with acceptable accuracy.

Conflict of interest statement

None declared.

Financial disclosure statement

Not applicable in the present work.

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